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NEW MADRID AND WABASH VALLEY SEISMIC STUDY: SIMULATING THE IMPACTS ON NATURAL GAS TRANSMISSION PIPELINES AND DOWNSTREAM MARKETS

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ABSTRACT

This paper summarizes the methodology, simulation tools, and major initial findings made by Argonne National Laboratory (Argonne) on the potential impact of simultaneous, high-intensity New Madrid and Wabash Valley Seismic Events on the natural gas interstate pipelines and their subsequent impacts on the downstream customers, particularly on the states under the purview of the Federal Emergency Management Agency (FEMA) Region V operations. Downstream impacts are expressed in terms of percent reduction in deliveries, population affected, and numbers of commercial and industrial customers shed. Damage functions and fragility curves are employed to identify specific pipelines that could potentially be affected, as well as the probable location(s) of the pipeline breaks and leaks. Effects of emergency remedial measures to mitigate impacts are also simulated. The methodology employed two models: (1) the FEMA-developed *HAZUS MH-MR3* and (2) the Argonne-developed *NGFast* pipeline break simulation tool. The models are described, and their complementary roles are discussed.

1 INTRODUCTION

This paper reflects the recent work performed for the Federal Emergency Management Agency (FEMA) Region V, Disaster Operations Division in Chicago, Illinois, in which Argonne National Laboratory (Argonne) was tasked to project the impacts of natural gas pipeline disruptions to downstream customers in the event of cascading New Madrid and Wabash Valley seismic events.

Concerns about the recurrence of a major seismic event in New Madrid heightened in recent months because of the "200-year-recurrence cycle" associated with the New Madrid Fault. A series of over 2,000 earthquakes were felt by the few pioneers that lived in the region from 1811 – 1812. Some of the strongest of these earthquakes were "recorded" at 7.7 and 6.8 (i.e., based on the Richter scale intensity index) in the New Madrid and Wabash Valley areas, respectively. Thus, it is prudent for disaster response agencies like FEMA to prepare for such potentially devastating events...

A brief review of the literature indicated that a number of studies have been made concerning the impacts of a major New Madrid seismic event in the Midwest (Corbet et al. 2007, Elnashai et al. 2008). However, the studies were found somewhat lacking in terms of the details they provided pertaining to interstate natural gas pipelines and their subsequent impacts to downstream areas (i.e., areas not local to the seismic zones). FEMA commissioned this study with five primary purposes in mind. These primary objectives are as follows:

- Assess impact(s), focusing on natural gas interstate transmission pipelines;
- Identify specific interstate pipelines affected;
- Identify probable location(s) of pipeline breaks;
- Assess downstream impacts in terms of population and numbers of business customers affected; and
- Estimate restoration timeframe(s) from the perspective of industry experts.

One other important aim of the study was to convey the concept, particularly to the FEMA Region V member states, that earthquake events not only impact the local areas where the faults exist but can easily cascade to other areas located downstream of the affected infrastructures, such as the interstate natural gas system. For these downstream impacts, specific disaster action plans would need to be developed by FEMA. In other words, states that are far away from New Madrid

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(e.g., Michigan, Wisconsin, and Minnesota) should understand the far-reaching impacts of the event and prepare appropriate disaster response plans. As an initial benefit, the results of the study were used by FEMA in its Region V New Madrid Seismic Zone Regional workshop held in Indianapolis, Indiana, on February 24, 2009. Because the primary goals have something to do with disaster scenario development and recovery, less emphasis is placed on the analysis of economic impacts.

In the official statement of work (SOW) provided by FEMA to Argonne, FEMA defined the scenario to be simulated as follows: The seismic event would occur on February 24 at 2:00 a.m., with the New Madrid Seismic Zone (NMSZ) exhibiting a magnitude 7.7 earthquake occurring in southern Illinois. The northern arm of the New Madrid Fault would rupture over a distance of tens of miles, generating intense shaking in southern Illinois and the boot heel of Missouri and a magnitude 6.8 earthquake along the Wabash Valley, with an epicenter located at 38.45N and 87.89W at a depth of 14.2 miles. Argonne was to determine the impacts as outlined and implied by the five primary objectives mentioned above. Figure 1 shows the general location of the New Madrid and Wabash Valley Seismic Zones.

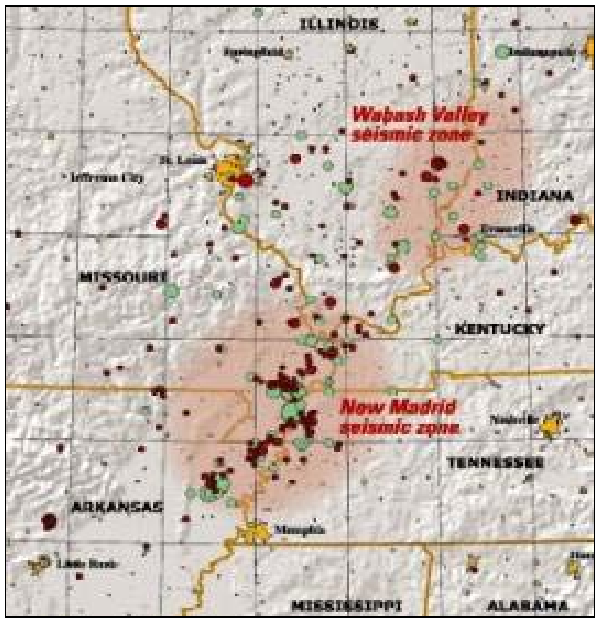

Figure 1: Map of the New Madrid and Wabash Valley seismic zones. Red circles indicate earthquakes that occurred from 1974 to 2002 with magnitudes larger than 2.5 on the Richter scale (USGS 2009).

2 METHODOLOGY

2.1 Data and Simulation Model Requirements

To accomplish the goals of the study, certain data sets, damage functions, and simulation models were identified and assembled by Argonne. The first data requirement pertains to earthquake hazards data, specifically, ground motion contours associated with the indicated events. As of this writing, three sets of ground motions data were provided by FEMA to Argonne to support the project. These data sets include (for both New Madrid and Wabash Valley):

- Permanent Ground Velocity (PGV) shake map,
- Peak Ground Acceleration (PGA) shake map, and
- Ground Liquefaction map.

Another data set, the permanent ground deformation (PGD) shake map, will also be provided by FEMA. PGV and PGD data sets are especially relevant for determining the numbers of leaks and breaks for buried pipeline systems, while PGA is relevant for assessing damage to vertical structures, such as buildings and compressor stations. The liquefaction maps are very important in identifying areas where the soil underneath the pertinent support structures could liquefy, cave in, and/or create damaging sink holes.

The second set of data requirements pertains to the inventory data sets for transmission pipelines and compressors stations that are in the vicinity of the fault lines. Argonne provided the needed data sets for this requirement.

The third set of data requirements involved damage functions and models that can simulate damage to pipelines and their ensuing impacts to downstream markets served by these interstate pipelines. Two simulation models were chosen by Argonne to be employed in the study. These are:

- HAZUS MH-MR3, a multi-hazard loss estimation earthquake model; and
- NGFast, a rapid assessment tool for simulating pipeline breaks and assessing downstream impacts.

These two models are described in the following sections.

2.2 HAZUS Model

The HAZUS was developed by FEMA for assessing potential equipment and building loss due to earthquakes. This model is primarily intended to simulate damage in the local area surrounding the earthquake's epicenter. The model is designed to produce loss estimates for use by federal, state, regional, and local governments in planning for earthquake risk mitigation and emergency preparedness, response, and recovery. The methodology deals with nearly all aspects of the built environment and a wide range of different types of losses. Extensive national databases are embedded within HAZUS that contain information, such as demographic aspects of the population in a study region, square footage for different occupancies of buildings, and numbers and locations of bridges. Embedded parameters have been included as needed. By using this information, users can carry out general loss estimates for a region. The HAZUS-MH methodology and software are flexible enough so that locally developed inventories and other data that more accurately reflect the local environment can be substituted, resulting in increased accuracy [FEMA 2003].

HAZUS employs the following empirically derived damage function to determine pipeline breaks and leaks:

$$RR = 0.0001 \text{ x } 0.3 \text{ x } (PGV)^{2.25}, \tag{1}$$

where:

PGV = permanent ground velocity in centimeters per second (cm/s)
RR = repair rate in repairs per kilometer (repairs/km)

Equation (1) applies to buried steel pipelines, which characterize most of the natural gas interstate pipeline systems passing through the New Madrid and Wabash Valley Areas. The proportionality constants were based on empirical data upon which (1) was fitted.

Once the repair rates are determined, the total number of repairs is calculated by multiplying the repair rate by the length of the pipelines segment in the hazard zone of specific constant intensity. Finally, the numbers of leaks and breaks are established by assuming that for steel natural gas pipelines, 90% of the total repairs are leaks and the remaining 10% are breaks.

In HAZUS, damage functions are given for each pre-defined damage state. There are only two damage states for pipelines: leaks and breaks. However, there are four damage states for compressor stations defined in the HAZUS model. These are: minor, moderate, extensive, and complete. The damage functions for compressor stations are summarized in Table 1 below:

Table 1: Damage functions for large, anchored compressor stations.

Peak Ground Acceleration (PGA)			
Classification	Damage State	Median (g)	β
Compressor stations with anchored subcomponents	Slight/minor	0.15	0.75
	Moderate	0.36	0.65
	Extensive	0.77	0.65
	Complete	1.55	0.80

The PGA is usually expressed in units of "g," the earth's gravitational acceleration, which is roughly equal to 9.806 meters per second per second or 32 ft/sec^2. The median PGA is an important value because it indicates the point at which one damage state transitions to that of another damage state. In some literature, this point is called the seismic capability of the equipment for a certain damage level (Oikawai et al. 2001). The β symbol in Table 1 is the standard deviation of a log-normal distribution (also called a fragility curve) associated with a particular damage state. It is a kind of "fudge" factor inserted to account for other unknown factors affecting the accuracy of the functions. The standard deviation β affects the determination of the median PGA in the process of deriving the fragility curves.

The approach for estimating the location of the breaks involves segmenting the pipeline under consideration on the basis of the PGV intensity of the region traversed by each pipeline segment. An example of such a determination is shown in Figure 2. Thus, for each segment, Equation (1) was applied to determine the RR and, subsequently, the number of leaks and breaks in that segment.

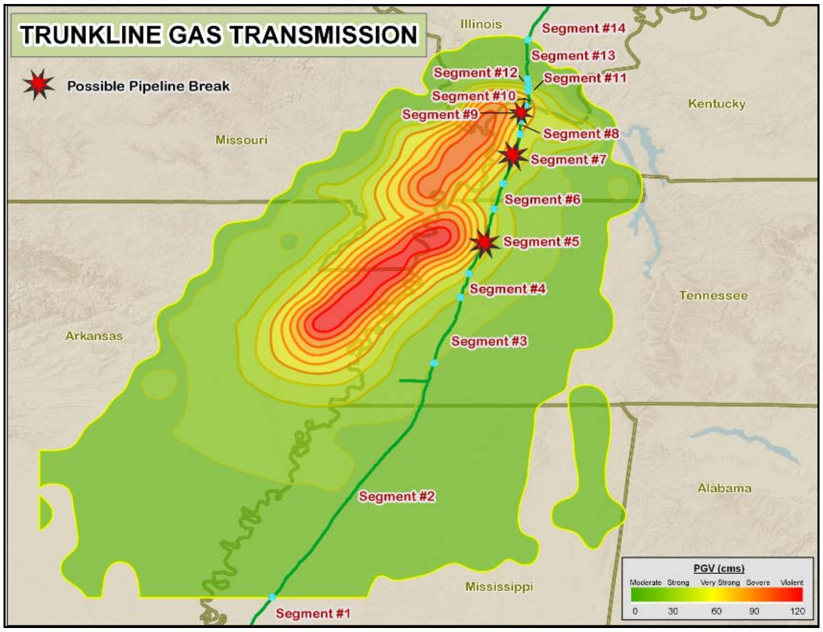

Figure 2: Example of the Trunkline Pipeline System segmented and analyzed to determine potential leaks and breaks. The PGV contours for New Madrid are also shown.

In Table 2, the application of the methodology resulted in breaks identified for Segments, 5, 7, and 9. This result implies that Trunkline would have a 100% flow reduction in the vicinity of the seismic zone. A similar process is applied to all high-risk pipelines traversing the seismic zones.

Table 2: The Trunkline System is segmented into 14 parts. Equation (1) is subsequently applied to each segment. The Xs and Ys in columns 3–6 signify latitude and longitude values, respectively. The highlighted rows indicate occurrence of a break.

Age	Segment	FROM		TO		Length		PGV	R.R.	# Repairs	Leaks	Break
		Y	X	Y	X	Miles	Kilometer	cms	repairs/km			
after 1935	1	---	---	33.601	-90.720	---	---	6.6	0.002	1	0	0
after 1935	2	33.601	-90.720	35.312	-89.552	145.0	245.0	16.5	0.016	4	4	0
after 1935	3	35.312	-89.552	35.793	-89.356	36.0	57.9	27.5	0.052	3	3	0
after 1935	4	35.793	-89.356	35.964	-89.298	12.0	1.3	38.5	0.111	2	2	0
after 1935	5	35.964	-89.298	36.438	-89.116	36.0	57.9	49.5	0.195	11	10	1
after 1935	6	36.438	-89.116	36.622	-89.050	14.0	22.5	38.5	0.111	2	2	0
after 1935	7	36.622	-89.050	36.985	-88.927	26.0	41.8	49.5	0.195	8	7	1
after 1935	8	36.985	-88.927	37.083	-88.924	7.0	11.3	60.5	0.306	3	3	0
after 1935	9	37.083	-88.924	37.191	-88.886	8.0	12.9	71.5	0.446	6	5	1
after 1935	10	37.191	-88.886	37.301	-88.870	8.0	12.9	30.5	0.066	4	4	0
after 1935	11	37.301	-88.870	37.340	-88.867	3.0	4.8	38.5	0.111	1	1	0
after 1935	12	37.340	-88.867	37.389	-88.872	3.0	4.8	27.5	0.052	0	0	0
after 1935	13	37.389	-88.872	37.673	-88.871	20.0	32.2	16.5	0.016	1	1	0
after 1935	14	37.673	-88.871	---	---	---	---	6.6	0.002	0	0	0
TOTAL										45	42	3

In the absence of PGD shake maps, liquefaction maps may be used to locate the possible location(s) of pipeline breaks. To carry out this analysis, information from liquefaction maps is combined with information from PGA maps and the area traversed by the pipeline segment over a high-probability liquefaction zone.

2.3 NGFast Model

The NGFast model, in contrast to HAZUS, is designed to assess downstream impacts of the breaks, particularly, to FEMA Region V states (e.g., Illinois, Wisconsin, Minnesota, Ohio, and Michigan), including some northeast states as far as Pennsylvania and New York. NGFast is a linear model that simulates pipeline breaks and assesses their impacts on downstream markets. The NGFast tool is a national model that includes data on more than 80 interstate pipelines, more than 1,800 local distribution companies (LDCs), and nearly 800 state border points. These data represent approximately 98% of existing pipelines, about 90% of existing LDCs, and 100% of known border crossings. NGFast also contains a database on the technical characteristics and monthly activities of underground natural gas storage (UGS) facilities, liquefied natural gas (LNGs), and production fields.

NGFast uses a progressive forward pipeline ownership identification and flow quantification process to track lost flow volumes resulting from a pipeline break or curtailment in production. Heuristics are used to allocate load to be shed among affected LDCs and various types of consumers within those LDCs. Heuristics are also applied to estimate spare capacity from compensating pipelines, UGS facilities, LNG facilities, and production fields. The calculation starts at the upstream state most affected by the break and proceeds progressively toward the terminal (i.e., the most downstream) states. The special structure of the state border database (i.e., "from-state" and "to-state" fields) allows the calculation method to proceed following the flow of gas along the pipeline, analyzing each state in sequence as it is traversed by the pipeline. Figure 3 illustrates the forward flow quantification process for a simple single pipeline system traversing several states.

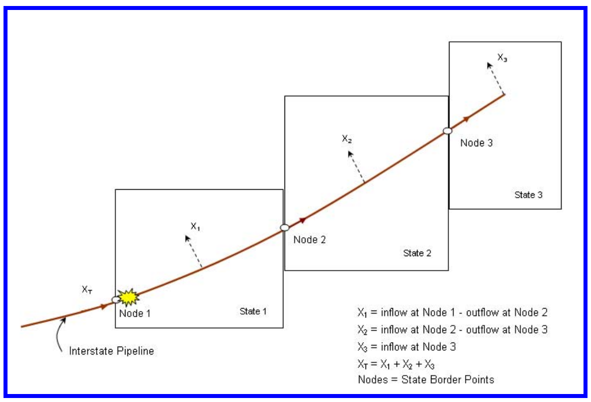

Figure 3: Forward flow and delivery quantification process in NGFast.

Under the uncompensated mode (i.e., a mode whereby no mitigation measures are invoked), when a state border node of a specific pipeline is assumed disrupted, the flow volume through that node (in millions of cubic feet per day [MMCFD]) is assumed lost. If the pertinent line traverses several states downstream of the disruption point, a multiple-state scenario computation must be performed, and the impacts on all the downstream states must be analyzed.

Should load shedding become imperative because of the gas curtailments, the following order of load shedding is observed by the pipeline companies and LDCs:

1. Natural gas-fired power plants.
2. Industrial customers.
3. Commercial customers.
4. Residential customers.

As much as is possible, the residential load is preserved to avoid fatalities. Some remedial actions that pipeline companies can take prior to undertaking permanent restoration work may include the following, besides selective shedding:

- Increased withdrawal from underground storage,
- Increased flow from interconnecting but unaffected pipelines,
- Increased withdrawal from LNG facilities, and
- Increased output from nearby production fields.

NGFast has both tabular and graphical output. The new version (Version 5) depicts the output by utilizing Google Earth's layers as shown in Figure 4.

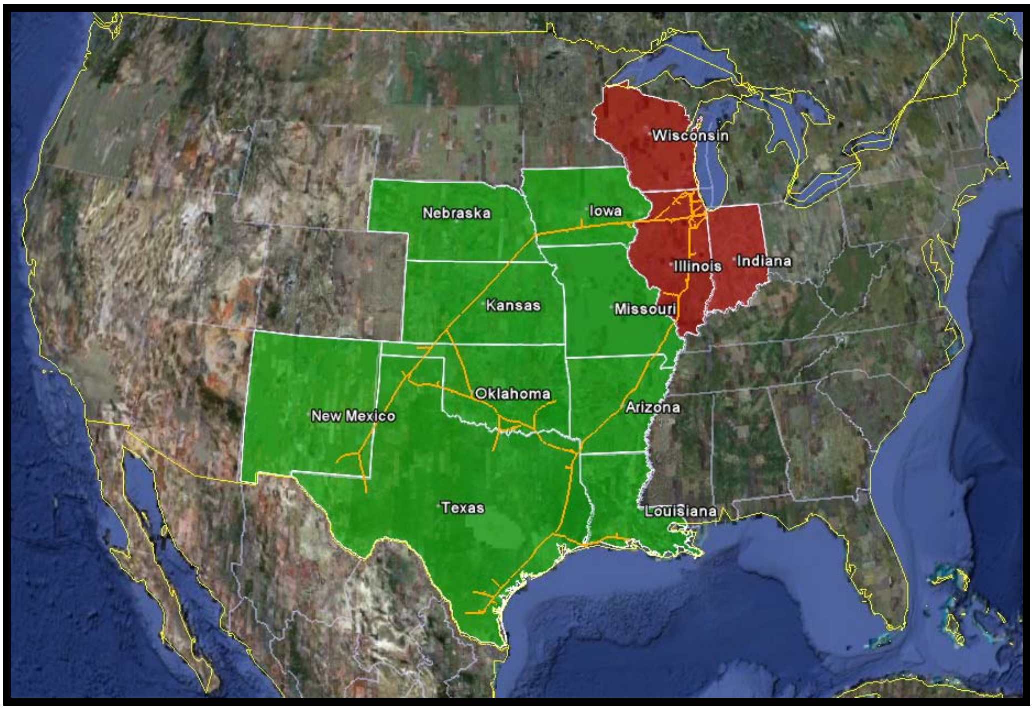

Figure 4: NGfast's new graphical output using geographical layers from Google Earth. Affected states are shown in red.

NGFast summary tabular output report includes:

- Downstream states affected,
- LDCs affected per state,
- Load shed per customer class per LDC,
- Number of customers per class type,
- MW of electric power plants affected,
- Detailed per state pre- and post-disruption load and flow levels, and
- Options on remedial actions to minimize overall impact(s).

2.4 Flowchart of Methodology

The steps for conducting the study are summarized and depicted schematically in Figure 5. The process is straightforward with minimal iteration work. Manual interventions are made to ensure that intervening analysis outputs are valid, reasonable, and logical.

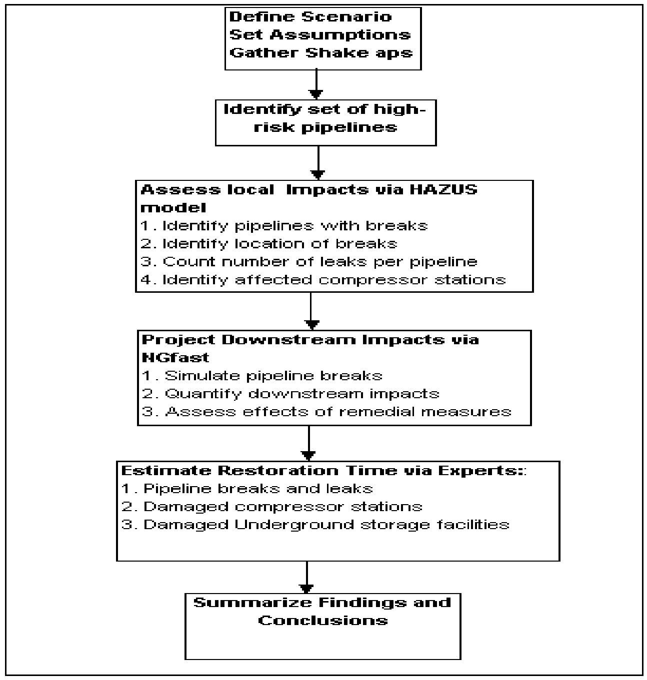

Figure 5: Steps in the Methodology.

3 INPUT DATA DESCRIPTION

3.1 FEMA Shake Maps

A shake map is another term used to refer to ground motion data. The PGV contours provided by FEMA for New Madrid and Wabash Valley are depicted in Figures 6 and 7, respectively. The contoured PGA as well as liquefaction maps for the two areas were available but are not depicted here because of space considerations. Contoured shake maps are also called simplified shake maps because they levelize the PGV or PGA values over an entire zone or layer surrounding the epicenter.

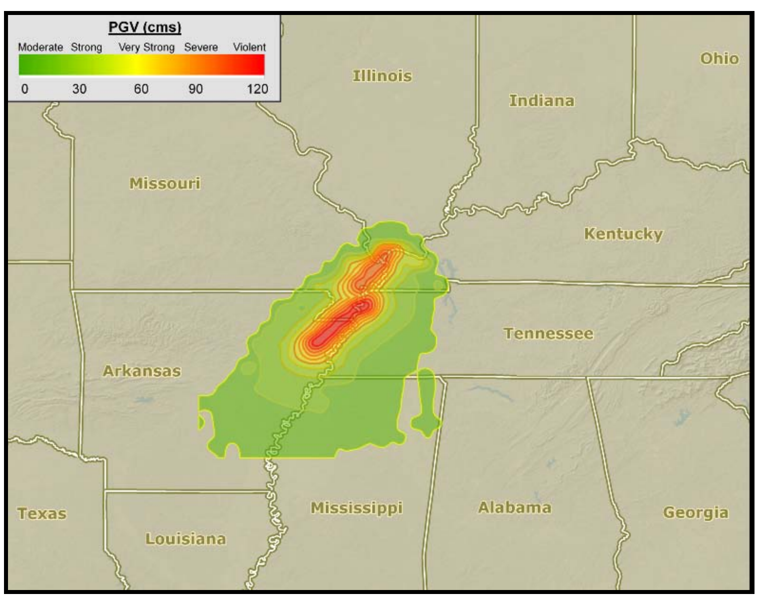

Figure 6: The PGV contours in the New Madrid Seismic Zone.

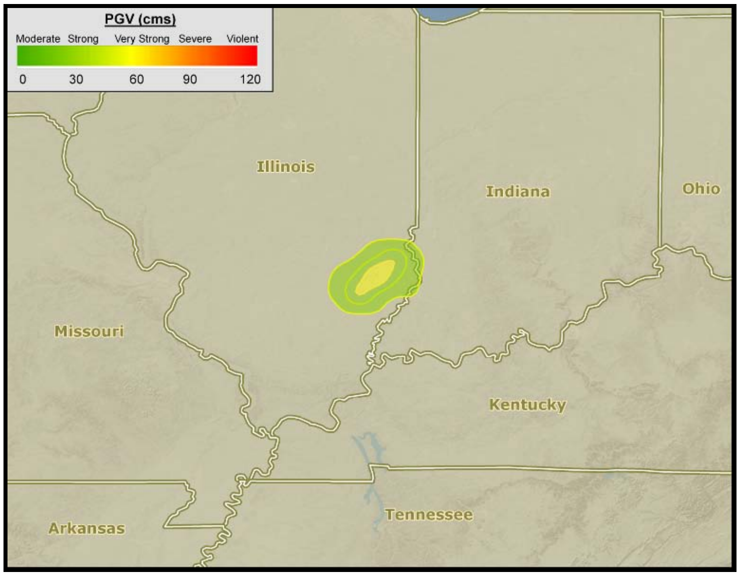

Figure 7: The PGV contours in the Wabash Valley Seismic Zone.

3.2 NGFast Database

The NGFast database contains graphical (shape files) and quantitative gas flow information on more than 80 interstate pipelines and on more than 1,800 LDCs. The pipeline graphical layouts are based on the U.S. Department of Transportation's (DOT's) National Pipeline Mapping System (NPMS). Figure 8 shows the 10 interstate pipeline systems identified as being high risk to experience damage from the New Madrid and Wabash Valley Seismic Events using NGfast's NPMS-sourced database.

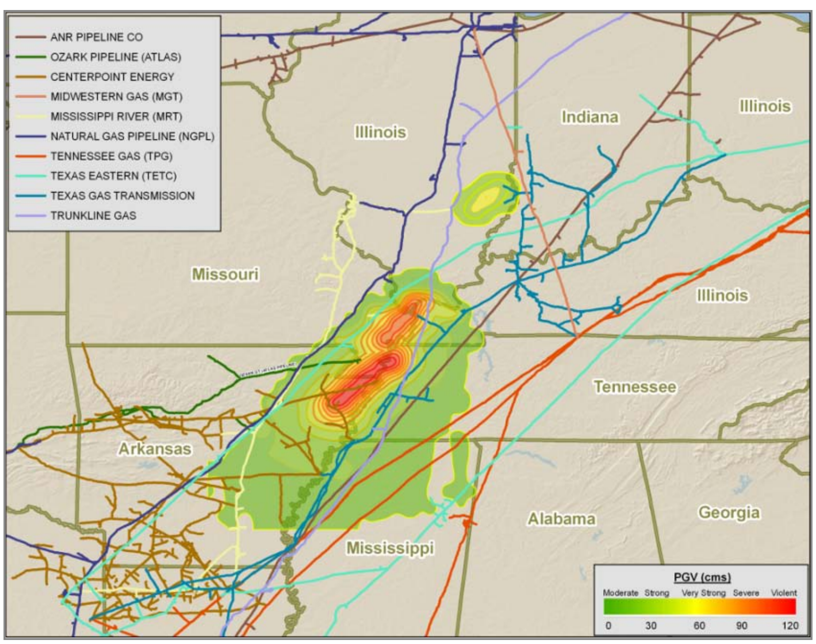

Figure 8: Layout of the 10 high-risk pipeline systems are depicted using NGfast's NPMS database.

NGFast uses the Energy Information Administration's (EIA's) state border files to assess flow levels through the pipelines in the vicinity of the fault zones during the month of February. Table 3 summarizes the estimated flow levels, capacities, and monthly utilization factors of the major interstate pipelines in the New Madrid and Wabash Valley seismic zones.

Table 3: Estimated flow levels and capacities through the pipelines in areas near the New Madrid and Wabash Valley fault zones.

Name of Interstate Pipeline	Flow (MMCFD)	Capacity (MMCFD)	Utilization Factors (%)
ANR Pipeline	982	1,753	56
Centerpoint Energy	349	650	54
Ozark Pipeline	197	355	55
Midwestern Gas Transmission	444	565	79
Mississippi River Transmission	372	730	51
Natural Gas Pipeline Company	977	1,574	62
Tennessee Gas Pipeline	1,470	1,632	90
Texas Eastern Transmission	252	324	78
Texas Gas Transmission	1,495	1,980	76
Trunkline Gas Company	640	1,570	41

It may be noted in Table 3 that the estimated utilization factors range from 41%–90% among the pertinent pipeline systems. The monthly state border flows were estimated by NGFast on the basis of the receiving state's state-level, normalized monthly natural gas consumption profile.

3.3 Monthly State-level Natural Gas Load Profile and Gas Storage Activities

NGFast contains estimates of the monthly natural gas usage of all 50 U.S. states and the District of Columbia. The monthly variation in natural gas consumption is an important consideration in the scenario development process and simulation phase, because gas usage could increase by a factor of up to 5 during winter relative to usage during the summer time. Figure 9 depicts the monthly natural gas use variations among the FEMA Region V states in 2006. It may be noted in Figure 9 that natural gas use tends to peak in February for all the Region V states.

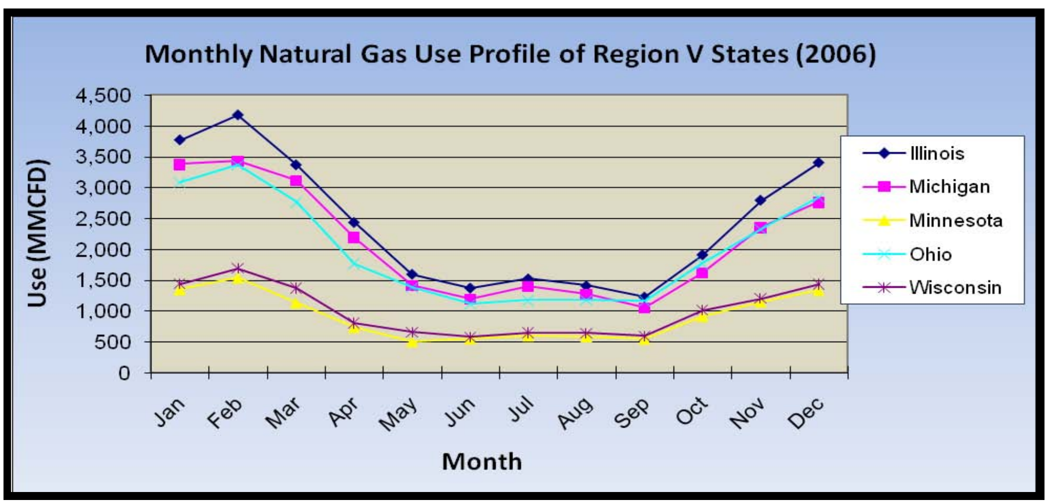

Figure 9: Monthly variations in natural gas use in the FEMA Region V states in 2006.

NGFast also contains information on monthly injection and withdrawal activities for all states that operate UGS facilities. Two of FEMA Region V states that have a significant number of UGS facilities are Illinois and Indiana. Figure 10 shows the UGS activities in these two states in 2006. It may be noted in Figure 10 that maximum withdrawals occur in February, making the UGS highly strained during that month. During the month of February, experts say that UGSs could be stressed further but no more than between 10% to 20% of their February withdrawal levels.

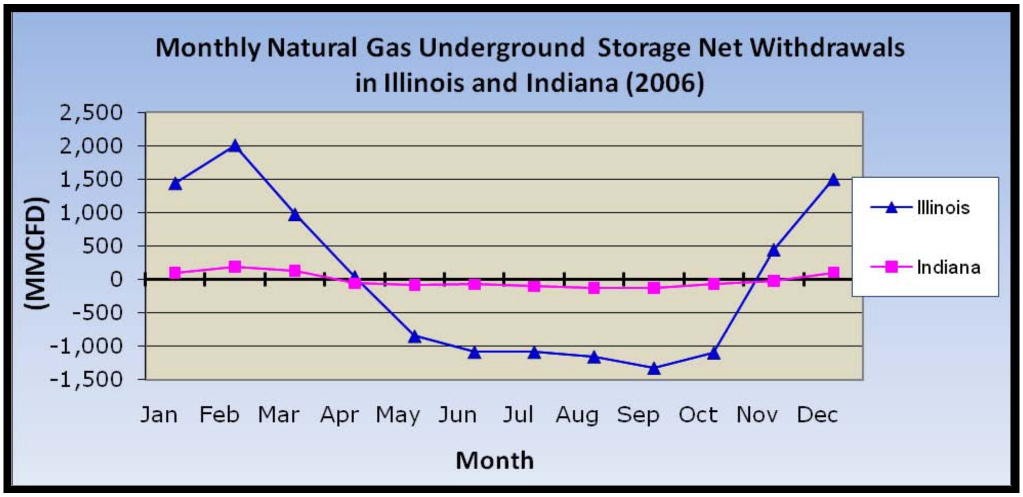

Figure 10: Monthly variations in natural gas storage net withdrawals in Illinois and Indiana.

4 MAJOR ASSUMPTIONS

While there are many assumptions used in this study, the major ones are highlighted in this section to help enable readers to have a better understanding of the analysis outputs. The following are the major assumptions:

- The buried pipeline in the vicinity of the New Madrid and Wabash Valley seismic zones are assumed to be made of steel, generally ductile; are arc welded; and buried 4 to 6 feet below the ground surface. As of this writing, efforts are under way to contact the operators and owners of the affected pipelines to verify these assumptions. Generally, pipelines constructed after 1935 may be considered ductile.
- A pipeline segment break triggered by the earthquake implies a 100% flow reduction along that pipeline. This assumption is generally accepted because of the presence of check valves that shut off automatically in both the upstream and downstream sides of the break. The intention of the "shut-off" action is to isolate the break and prevent further loss of gas from the pipeline.
- The order of load shedding under force majeure conditions follows standard industry guidelines as follows: interruptible direct-connect loads, electric power, industrial, commercial and industrial loads, and finally, if absolutely necessary, residential loads. As a general rule, residential loads should be protected from load shedding as much as possible.
- Emergency remedial measures will be implemented in a well-coordinated fashion by pipeline operators, utilities, and government regulators to minimize overall impact(s) of the event.

5 KEY FINDINGS

The following are the initial key findings of the study. It must be emphasized that these findings are preliminary but indicative of the direction of the final conclusions:

1. Ten major natural gas interstate pipelines would be damaged by at least one break and several leaks as a result of PGA, PGV, and liquefaction with implications on Region V states. A total of 315 leaks and 49 breaks were determined. Two compressor stations and two UGS facilities were identified as potential installations that would experience some damage, ranging from slight to extensive.
2. All FEMA Region V states, except Minnesota, would experience substantial delivery reduction, ranging from 2% up to 18%. Rankings by states are as follows:
   Indiana: ~ 18%; Illinois: ~13%; Ohio: ~12%; Wisconsin: ~2%; Michigan: ~ 2%
   Other non-Region V states could experience up to 27% reduction in delivery.
3. Implementation of emergency remedial measures could limit the number of people affected to between about 60,000–100,000 (or 20,000–33,000 households) across several states; a large number of electric, industrial, and commercial customers (50,000–140,000) would also be shed (Figure 11).

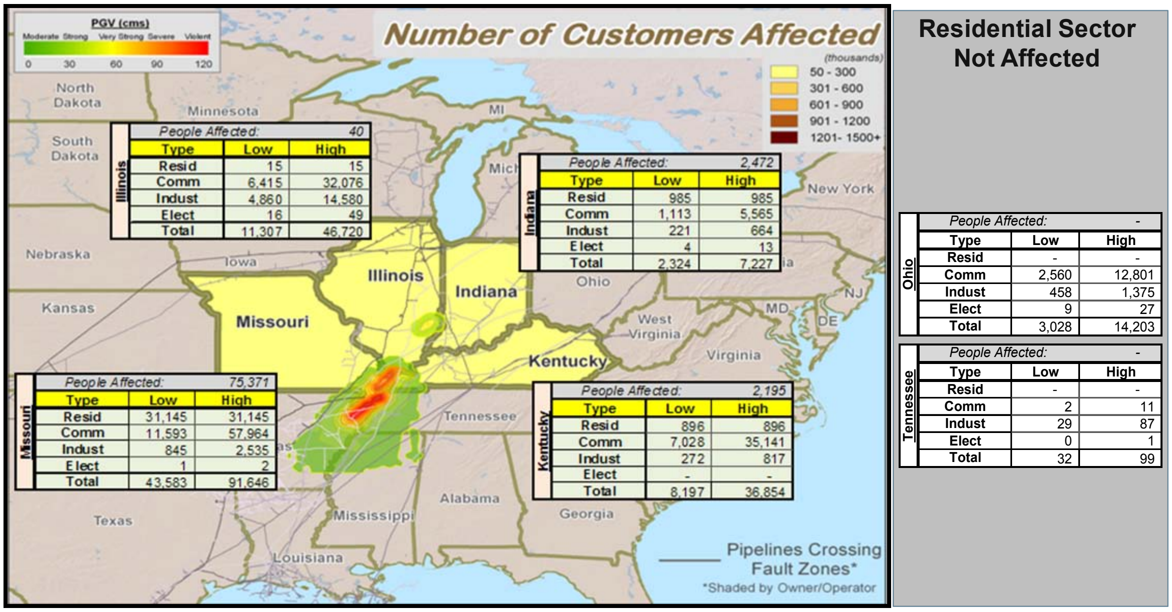

Figure 11: Downstream impacts in terms of affected population and numbers of industrial and commercial customers.

4. A well-orchestrated implementation of remediation measures would limit impacts on natural gas-fired power to low levels (less than 2% of installed capacity).
5. In general, only two UGS facilities would experience any serious damage (i.e., that would make them non-operational).
6. Restoring damaged pipelines to full functionality would take about 1–3 months, depending on: (a) how the pipeline companies subdivide and "phase" the work, (b) the availability of crews, (c) conditions of access roads, and (4) resolved target completion times; restoration for residential and industrial customers would take between 2–4 weeks and 4–8 weeks, respectively.

6 CONCLUSIONS

The study has shown a viable methodology for simulating the local as well as the downstream impacts of the New Madrid and Wabash Valley seismic events in relation to the natural gas interstate pipeline systems running through the vicinity of the quakes' epicenter. It has also been shown that it is possible to identify the specific sets of high-risk pipelines and the locations of the corresponding breaks. The study has also shown the complementary roles of the *HAZUS* and *NGFast* models in analyzing both the nearby as well the far-reaching effects of high-intensity seismic events, such as the potential (or projected) New Madrid and Wabash Valley earthquakes. *HAZUS* can locate pipeline breaks and leaks while *NGfast* can quantify downstream impacts in terms of the percent reduction in natural gas deliveries, the residential population affected, and the numbers of commercial and industrial customers shed. The results of the study could be used for quantifying economic impacts in monetary terms. Most important, the results could aid FEMA in its current as well as future disaster response and recovery planning activities.

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